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NUMERICAL STUDY ON ALUMINIUM LIPPED CHANNEL SECTIONS SUBJECTED TO WEB CRIPPLING UNDER TWO-FLANGE LOAD CASES

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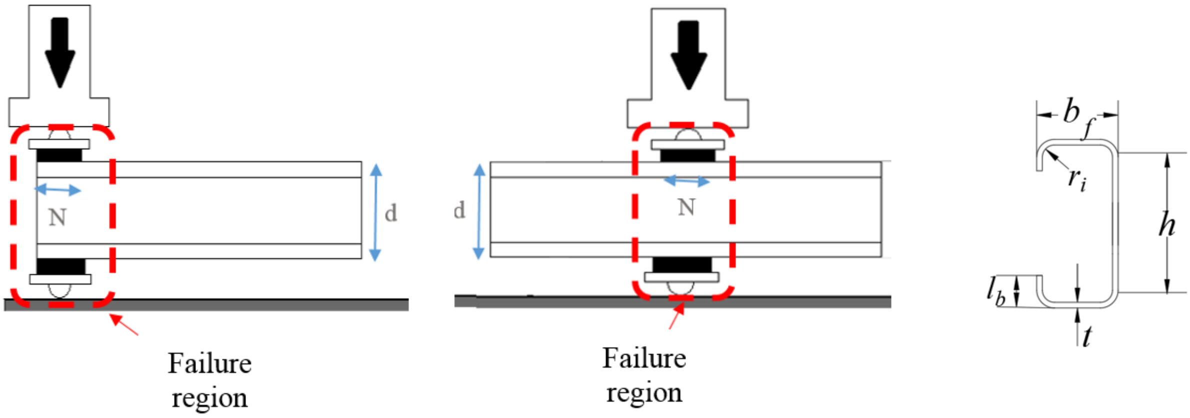
Abstract. *The use of thin-walled aluminium alloy members in construction has significantly increased during the recent years due to its appealing characteristics. However, they are highly susceptible to web crippling failure due to its lower elastic modulus. In addition to the experimental study conducted by the authors, a numerical study was carried out to further investigate the web crippling phenomenon of unfastened aluminium lipped channel sections under two flange load cases. Subsequently, a detailed parametric study was conducted to thoroughly investigate the web crippling bearing capacities of a wide range of aluminium lipped channel sections including different material properties, sectional geometric parameters and bearing lengths. The extensive FE web crippling capacity data were then used to assess the accuracy of the web crippling design rules provided by the Australian design guidelines for aluminium structures. It was found that the current equations are unconservative and unreliable to predict the web crippling capacity of aluminium lipped channel sections under two flange load cases. Thus, suitable modifications were proposed to the current web crippling design equation. It is shown that the modified design rules closely predicted the web crippling strengths for aluminium lipped channel sections.*

Keywords: Aluminium; lipped channel sections; web crippling; numerical study; design rules.

1 INTRODUCTION

Roll-formed aluminium flexural members are subject to various failures modes including bending, shear, torsion and web crippling. When they are subjected to concentrated loads and reactions under different load conditions, thin-walled aluminium members suffer from web crippling failure. Lipped Channel sections are vulnerable to this kind of failure especially those unstiffened against this type of loading. The literature review shows that the computation of web crippling capacity in theoretical approach is rather complex since it involves many factors such as the instability of the web element and the local yielding in the loading region (Keerthan et al. 2014). Hence, the currently available design rules for web crippling in most aluminium and steel structures specifications are empirical in nature and developed based on a large number of experimental tests.

To investigate the web crippling behaviour of cold-formed members, the AISI Standard test method (2008) introduces four different loading cases that the member is potentially subjected to in real-life applications. These cases are classified according to the loading and reaction locations such as end columns, interior columns and joists supported by bearers. They are: End-Two-Flange (ETF), Interior-Two-Flange (ITF) load cases, End-One-Flange (EOF), and Interior-One-Flange (IOF) load cases. Figure 1 presents the two flange load cases for web crippling.



(a) ETF load case (b) ITF load case (c) Typical cross section

Figure 1 Two flange load cases for web crippling.

2 AS/NZS 1664.1 DESIGN RULES

The web design rules for flat webs subjected to a concentrated transverse load are specified in Section 4.7.7 in the AS/NZS 1664 Standard (1997), Part 1 for aluminium structures. The nominal web crippling capacity (P_{AS}) is calculated based on Equations (1) and (2) for the ETF and ITF load cases, respectively.

$$P_{AS} = \frac{1.2t^2 \sin\theta(0.46f_y+0.02\sqrt{Ef_y})(N+C_{w2})}{C_{w3}+r_i(1-\cos\theta)} \quad \text{(ETF)} \qquad (1)$$

$$P_{AS} = \frac{t^2 \sin\theta(0.46f_y+0.02\sqrt{Ef_y})(N+C_{w1})}{C_{w3}+r_i(1-\cos\theta)} \quad \text{(ITF)} \qquad (2)$$

where $C_{w1} = 140mm$; $C_{w2} = 33\ mm$; $C_{w3} = 10\ mm$; N is the bearing length (mm); f_y is the static 0.2% yield stress (MPa); E is the elastic modulus (MPa); t is the thickness of the web (mm); r_i is the inside corner radius (mm) and θ is the angle that is calculated from the bearing surface plane to the plane of the web surface. Note that θ is 90° degree for the lipped channel sections used in this study.

3 EXPERIMENTAL INVESTIGITION

An experimental study comprising 38 tests was conducted by the authors (Alsanat et al. 2018) to investigate the web crippling behaviour of roll-formed aluminium lipped channel sections under ETF and ITF load cases. The aluminium sections were roll-formed from a well proven marine grade structural aluminium alloy 5052 H36 and Table 1 summarises the material properties of the specimens. Tables 2 and 3 present the test specimen details including five lipped channel sections and four bearing lengths (25, 50, 100 and 150 mm) and the experimental bearing capacities ($P_{Exp.}$) for each load cases.

Table 1 Mechanical properties of the aluminium sections (Alsanat et al. 2018).

Section	E_0 (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_u (%)
10030	65.05	210	259	6.15
15030	63.55	206	248	5.55
20025	63.95	214	260	5.05
20030	64.13	212	257	6.47
25025	64.34	216	265	6.68

Table 2 Test specimen details and results for ETF load case.

Specimen	d (mm)	b_f (mm)	l_b (mm)	t (mm)	r_i (mm)	L (mm)	$P_{Exp.}$ (kN)	P_{FEA} (kN)	$P_{Exp.}/P_{FEA}$
ETF-10030-N25	107.3	60.4	14.9	2.95	4.9	316	6.19	5.85	1.06
ETF-10030-N50*	106.5	58.4	16.1	2.95	5.0	317	6.23	6.46	0.97
ETF-10030-N100	107.3	59.4	15.0	2.95	4.8	316	7.41	7.83	0.95
ETF-15030-N25	156.7	62.8	22.9	2.93	4.9	466	5.23	5.41	0.97
ETF-15030-N50	157.5	63.3	22.4	2.93	5.0	465	5.50	5.74	0.96
ETF-15030-N100	158.3	63.5	21.7	2.92	5.1	465	6.37	6.48	0.98
ETF-15030-N150	155.5	63.5	22.9	2.92	4.9	467	7.25	7.62	0.95
ETF-20025-N25	208.1	74.6	25.5	2.42	5.1	617	3.33	3.34	1.00
ETF-20025-N50	208.1	74.2	25.4	2.43	4.9	615	3.61	3.48	1.04
ETF-20025-N100	207.3	74.3	25.7	2.43	5.0	615	3.92	3.78	1.04
ETF-20025-N150	204.0	75.8	26.5	2.43	4.8	615	4.23	4.30	0.98
ETF-20030-N25	204.6	74.9	27.4	2.9	4.6	611	4.95	5.11	0.97
ETF-20030-N50	208.4	73.0	27.5	2.9	5.0	615	5.07	5.22	0.97
ETF-20030-N100	204.5	75.4	27.7	2.89	4.6	613	5.82	5.91	0.98
ETF-20030-N150	208.3	73.5	27.1	2.89	5.0	615	6.06	6.40	0.95
ETF-25025-N25	259.8	80.8	23.4	2.43	4.4	765	2.95	3.01	0.98
ETF-25025-N50	259.9	76.1	23.7	2.44	4.9	765	3.09	3.11	0.99
ETF-25025-N100	262.1	76.2	22.7	2.44	4.8	765	3.76	3.36	1.12
ETF-25025-N150	260.3	76.3	23.4	2.45	4.6	765	4.15	3.69	1.12
Mean									**1.00**
COV									**0.05**

* Note: ETF-10030-N50 specimen was repeated to validate the test procedure.

Table 3 Test specimen details and results for ITF load case.

Specimen	d (mm)	b_f (mm)	l_b (mm)	t (mm)	r_i (mm)	L (mm)	$P_{Exp.}$ (kN)	P_{FEA} (kN)	$P_{Exp.}/P_{FEA}$
ITF-10030-N25	106.9	59.3	14.3	2.94	4.8	527	21.40	22.05	0.97
ITF-10030-N50*	106.4	59.4	14.8	2.95	4.9	525	18.90	18.00	1.03
ITF-10030-N100	106.1	59.6	14.4	2.94	4.8	523.5	18.29	18.57	0.98
ITF-15030-N25	156.5	62.6	22.6	2.93	4.8	774	18.71	18.49	1.01
ITF-15030-N50	156.7	62.4	22.7	2.92	4.9	775	18.29	18.00	1.02
ITF-15030-N100	156.2	62.1	22.7	2.92	4.8	776	18.00	18.45	0.98
ITF-15030-N150	156.6	62.5	22.8	2.93	4.9	774	18.30	19.35	0.95
ITF-20025-N25	206.2	74.0	26.3	2.43	4.6	1028	12.82	12.39	1.03
ITF-20025-N50	207.2	73.3	26.0	2.44	4.9	1022	12.23	12.55	0.97
ITF-20025-N100	207.3	73.9	26.3	2.43	5.0	1019	12.19	12.32	0.99
ITF-20025-N150	207.4	73.4	26.9	2.44	4.6	1021	12.27	12.53	0.98
ITF-20030-N25	205.6	74.5	31.6	2.9	4.4	1022	18.12	18.43	0.98
ITF-20030-N50	206.6	75.3	27.4	2.93	4.8	102	18.00	18.50	0.97
ITF-20030-N100	206.5	74.4	26.7	2.9	4.8	1021	17.59	17.74	0.99
ITF-20030-N150	206.5	74.5	26.7	2.89	4.6	1022	17.62	19.35	0.91
ITF-25025-N25	259.9	76.1	22.1	2.43	4.4	1273	12.08	11.81	1.02
ITF-25025-N50	260.0	76.0	22.4	2.42	4.5	1274	11.79	11.58	1.02
ITF-25025-N100	259.8	76.3	22.5	2.43	4.5	1269	11.77	11.73	1.00
ITF-25025-N150	259.9	76.2	22.2	2.43	4.5	1275	11.91	11.97	0.99
Mean									**1.00**
COV									**0.03**

* Note: ITF-10030-N50 specimen was repeated to validate the test procedure.

4 NUMERICAL INVESTIGATION

4.1 Model Development

In order to simulate aluminium lipped channel sections subjected to web crippling, the finite element analysis program ABAQUS version 6.13 was used. It provides advanced finite element analysis capabilities including geometric characteristics, nonlinear material and contact elements, which are crucial in the web crippling investigation. The quasi-static analysis method was used in this study to investigate the web crippling behaviour of aluminium lipped channel section due to its ability to overcome the convergence and contact difficulties (Natario et al. 2014). The FE models in this study consist of three main components namely: aluminium lipped channel section, the bearing plates and the interfaces between them. It should be mentioned that the measured cross-section dimensions and material properties were used in the FE analysis.

4.1.1 Finite Element Type and Mesh Control

The aluminium lipped channel sections were modelled using the S4R shell elements as recommended by Sundararajah et al. (2017). According to the ABAQUS Manual (Version 6.13, 2014), S4R element suitable for complex buckling analysis and provides accurate solutions to most shell element applications. The rigid bearing plates were modelled using R3D4 element which is a 4-node 3-D bilinear rigid quadrilateral element. Suitable mesh sizes for web, flanges and the corners were selected depending on the result accuracy and the computational time of the analysis. The finite element mesh size of 5x5 mm was used for the flanges and the web while finer mesh (5 x 1 mm) was used for the corners of the section to ensure proper transferring of the load from the flange to the web of the specimen.

4.1.2 Boundary Conditions and Interface Definition

The Boundary conditions were assigned to the reference points used to represent the bearing plates. The boundary conditions assigned to ETF models are similar to those applied on ITF models. As shown in Figure 2, all degree of freedom expect rotational degree about X-axis were restrained at the bottom support plate. The top loading plate was prevented from translational displacement in the X and Z direction and rotation about Y and Z axes. However, it was allowed to move vertically (Y direction). The interfaces between the bearing plates (Master) and the aluminium section (Slave) were modelled using the contact pair algorithms. The contact formulation was assumed to be “Hard” in the developed FE-models as the bearing plates were undeformable.

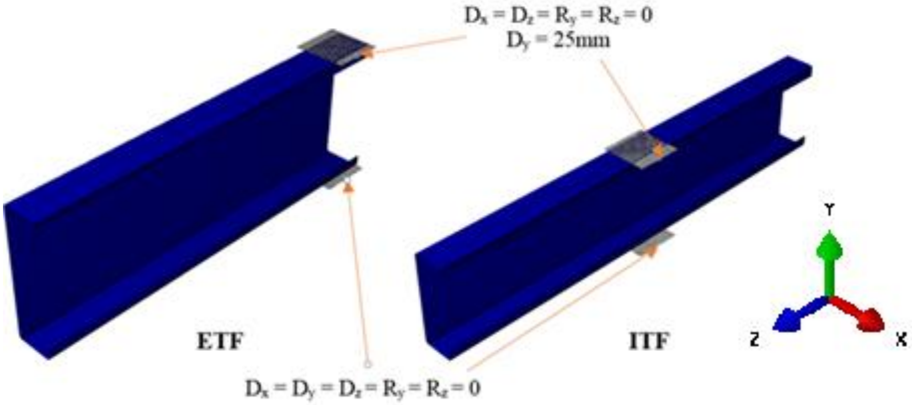


Figure 2 Contact surfaces and boundary conditions for ETF and ITF models.

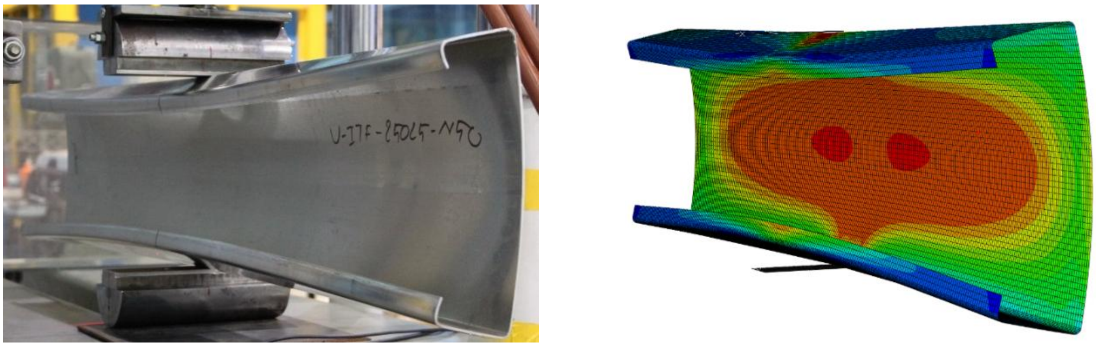
4.1.3 Material Properties

The material model of the specimens, which were measured from the coupon tests by Alsanat et al. (2018), were used in the FE analysis. Since high plastic strains are expected to occur in web crippling problems, it is recommended to convert the usual (engineering) stress–strain curve to a true stress–logarithmic strain curve. In this study, the stress and strain values, which obtained from engineering stress-strain curves, were converted to true stress and logarithmic plastic strain values and then used to stimulate the models for validation purposes. For parametric study, however, bilinear material model for aluminium developed by (Zhao et al. 2017) were considered.

4.2 Model Validation

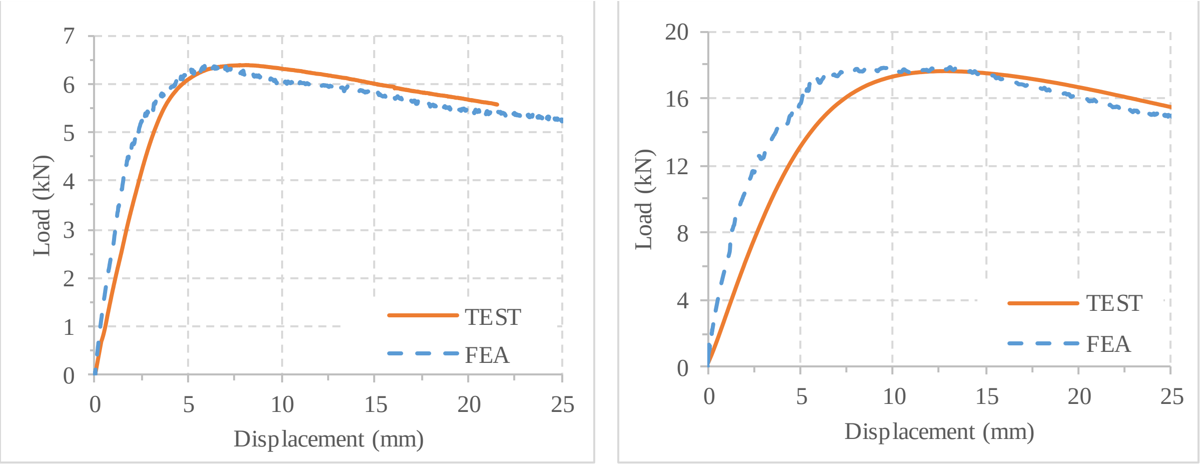
A total of 38 aluminium lipped channel sections subjected to web crippling were numerically analysed and compered with the experimental results. The main objective of the comparison is to verify and check the accuracy of the FE models. Tables 2 and 3 show a good agreement between the experimental results ($P_{Exp.}$) and the numerical results (P_{FEA}) of web crippling strengths for both ETF and ITF load cases, respectively. The mean value of the $P_{Exp.}/P_{FEA}$ ratio is 1.00 with the corresponding COV value of 0.05 for the ETF load cases while they are 1.00 and 0.03 for the ITF load case. Figures 3 (a) and (b) show the failure modes of ETF20025N50 and ITF25025N50 specimens, respectively, as observed from experiments and FE analysis. The load-deflection curves derived from FE analysis were also compared with the experiments as presented in Figures 4 (a) and (b) for ETF15030N100 and ITF20030N150 specimen respectively. Generally, it is shown that the FE models are able to reasonably predict the experimental web crippling strengths, load-web deformation curves and failure modes of aluminium lipped channel sections under two flange load cases.

(a) ETF20025N50



(b) ITF25025N50

Figure 3 Experimental and FEA failure modes of (a) ETF20025N50 and (b) ITF25025N50 specimens.



(a) (b)

Figure 4 Comparison of load versus vertical displasment plots of (a) ETF15030N100 and (b) ITF20030N150 specimens.

4.3 Parametric Study

In this study, a detailed paramedic study has been carried out to thoroughly investigate the web crippling phenomenon of aluminium lipped channel section under the two flange load cases. The validated FE models were used as a base of the parametric study to create an extensive database of web crippling capacities. These data was then used to improve the currently available design rules to accurately predict the web crippling capacities. Table 4 shows the details of parametric study conducted for aluminium lipped channel section under the ETF and ITF load cases. In order to investigate the effect of different material properties and sectional geometric on web crippling capacities, different bearing lengths (N = 25, 50, 100 and 150 mm), inside bent radius (r_i = 0, 2, 5 and 10 mm) were considered in the parametric study. Further, three different aluminium alloy grades: 5052-H32 (f_y = 145 MPa, E = 70 GPa), 5052-H36 (f_y = 179MPa, E = 69.3 GPa) and 5052-H38 (f_y = 207 MPa, E = 70.3 MPa) were also included in this study to investigate the effect of different aluminium grades. Total of 222 models were developed for ETF load case, and 296 models for ITF load case.

Table 4 Parametric study of aluminium lipped channel sections under the ETF and ITF load cases.

	ETF				ITF			
Section	N (mm)	r_i (mm)	f_y (MPa)	No. of Models	N (mm)	r_i (mm)	f_y (MPa)	No. of Models
10025	25, 50, 100,150	0,2,5,10	145,179,207	36	50, 100,150	0,2,5,10	145,179,207	48
10030		0,2,5,10	145,179,207	36		0,2,5,10	145,179,207	48
15025		2,5,10	179	9		2,5,10	179	12
15030		2,5,10	179	9		2,5,10	179	12
20025		0,2,5,10	145,179,207	36		0,2,5,10	145,179,207	48
20030		0,2,5,10	179	12		0,2,5,10	179	16
25025		2,5,10	179	9		2,5,10	179	12
25030		0,2,5,10	179	12		0,2,5,10	179	16
30025		0,2,5,10	145,179,207	36		0,2,5,10	145,179,207	48
30030		2,5,10	179	9		2,5,10	179	12
35030		2,5,10	179	9		2,5,10	179	12
40030		2,5,10	179	9		2,5,10	179	12
Total				**222**				**196**

5 MODIFIED AS/NZS 1664.1 DESIGN RULES

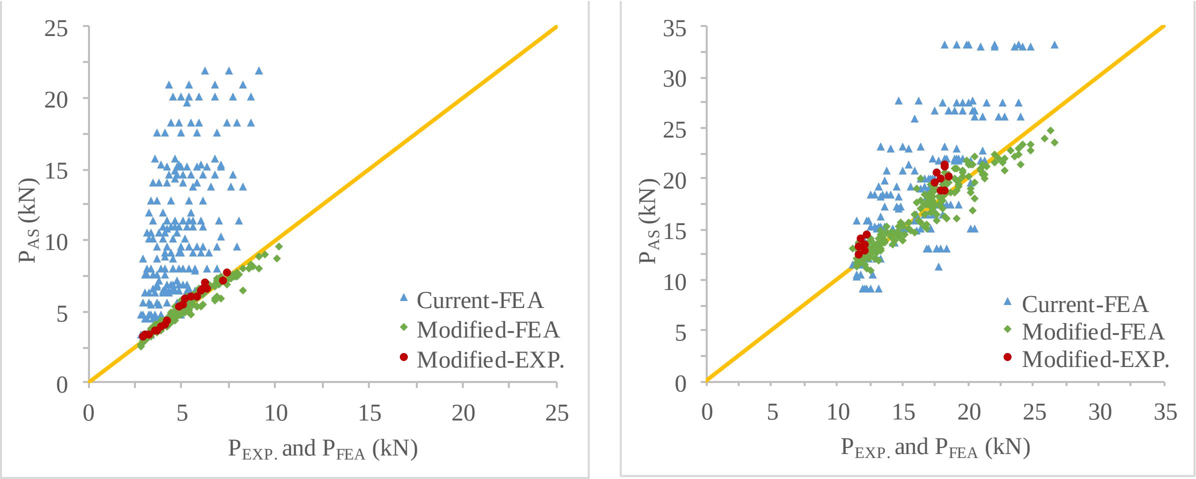
The web crippling prediction obtained from the AS/NZS 1664.1 (1997) design rules were compared with the extensive FE web crippling data. The mean values of the FEA-to-predicted web crippling capacity are 0.51 and 0.90, whereas the corresponding coefficient of variation (COV) values are 0.40 and 0.22 for the ETF and ITF load cases, respectively as shown in Table 5. This means that the web crippling predictions using the AS/NZS 1664.1 (1997) design equations is rather unconservative with unreliable COV values for aluminium lipped channel sections under both ETF and ITF load cases. Alsanat et al. (2018) improved these equations using their experiments, however; the modified equations are limited to ($29<h/t<95$), (r_i=5 mm) and aluminium alloy 5052-H36 grade. Equations (3) and (4), therefore, were proposed by modifying Equations (1) and (2) to expand their range of application in construction industry. It should be noted that the current design equations do not consider the effect of height-to-thickness ratio (h/t) in predicting the nominal web crippling capacity which has a significant influence in the web crippling capacity. Hence, the ratio (h/t) was introduced in Equations (3) and (4).

$$P_{AS(Modi.)} = \frac{0.052t^2 \sin\theta(0.46f_y+0.3\sqrt{Ef_y})(N+C_{w2})}{C_{w3}+r_i(1-\cos\theta)}\left(1-c_{h1}\sqrt{\frac{h}{t}}\right) \qquad \text{(ETF)} \qquad (1)$$

$$P_{AS\,(Modi.)} = \frac{0.117t^2 \sin\theta(0.46f_y+0.3\sqrt{Ef_y})(N+C_{w1})}{C_{w3}+r_i(1-\cos\theta)}\left(1-c_{h2}\sqrt{\frac{h}{t}}\right) \qquad \text{(ITF)} \qquad (2)$$

In which $C_{w1} = 780\ mm$; $C_{w2} = 480\ mm$; $C_{w3} = 25\ mm\ (ETF)$; $C_{w3} = 40\ mm\ (ITF)$ $C_{h1} = 0.05\ mm$ and $C_{h2} = 0.02\ mm$.

The modified Equations (3) and (4) can accurately predict the web crippling capacities of aluminium lipped channel sections under the ETF and ITF load cases, respectively. As shown in Table 5, the mean value of the FEA-to-predicted load ratio is 1.00 with the corresponding COV of 0.06, for the ETF load case while these values are 1.00 and 0.07 for the ITF load case. Figures 5 (a) and (b) show the web crippling capacity predictions using the current and modified AS/NZS 1664.1 (1997) Standard verses web crippling capacities obtained from the experiments and FEA for the ETF and ITF load cases, respectively.



(a) ETF load case (b) ITF load case.

Figure 5 Web crippling capacity predictions using the AS/NZS 1664.1 Standard verses web crippling capacities from the experiments and FEA: (a) ETF and (b) ITF Load cases.

Table 5 The mean and COV values for FEA/ AS1664.1.

Rules	Load case	Mean	COV
Current	ETF	0.51	0.40
	ITF	0.90	0.22
Modified	ETF	1.00	0.06
	ITF	1.00	0.07

6 CONCLUSION

A numerical investigation of aluminium lipped channel sections subjected to web crippling under the ETF and ITF load cases has been reported in this paper. 38 FE models were simulated using ABAQUS Software and analysed using quasi-static analysis. The essential stages of the development of finite element models were described in details. The FE models were then validated using the results obtained from Alsanat et al.'s (2018) experiments in terms of ultimate capacity, failure modes and load-deformation curves. Following the validation, a detailed parametric study was performed to create an extensive database of web crippling capacities of aluminium lipped channel sections for both ETF and ITF load cases. These numerical web crippling capacity data were compared with the nominal strengths calculated using AS/NZS 1664.1 (1997) Standard. It was found that the design strengths predicted by the aforementioned specification are quite unconservative and unsafe. Therefore, suitable improvements were proposed to these equations to accurately predict the web crippling capacities of aluminium lipped channel sections under two-flange load cases. The predictions obtained from the modified equation agree well with the web crippling data obtained from the FEA.

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